Use of Residual Compression in Design to Improve Damage Tolerance in Ti-6Al-4V Aero Engine Blade Dovetails

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ABSTRACT

The deep stable layer of compressive residual stress produced by low plasticity burnishing (LPB) has been demonstrated to improve the damage tolerance in engine alloys IN718, Ti-6Al-4V, and 17-4PH. This paper describes the application of LPB to the dovetail bedding surface of a Ti-6Al-4V fan blade to mitigate the adverse effects of fretting-induced microcracks. Blades removed from fielded engines were LPB processed to protect the dovetail region of the blade and specially designed feature specimens were used to simulate the dovetail region of the blades. Both feature specimens and actual dovetail sections were fatigue tested in cantilever bending mode at a stress ratio, R of 0.5 using specially designed test fixtures. Coalescing microcracks were simulated with electrical discharge machined (EDM) notches. Residual stress and cold work distributions were measured using x-ray diffraction mapping techniques.

LPB produced compression in the dovetail region up to a depth of 0.065 in. The HCF performance with EDM notches up to 0.040 in. deep was tested. LPB processed specimens with 0.020 in. deep EDM notch showed an endurance limit of 100 ksi, greater than that of the baseline undamaged surface. LPB treated blades and feature specimens with 0.030 in. and 0.040 in. deep notches showed endurance limits of 60 and 45 ksi, respectively. LPB was shown to fully mitigate the fretting debit, whether applied before or after the fretting damage occurred.

Linear elastic fracture mechanics analysis including the residual stress fields confirms the HCF performance in the presence of high residual compression. A novel approach for determining the residual stress field design to provide a desired fatigue life and microcrack tolerance is introduced.

INTRODUCTION

The Ti-6Al-4V 1st stage low pressure compressor blade dovetails of a military aircraft turbine engine have a reported fretting-induced microcracking problem in the edge-of-bedding, and are prone to cracking in this region. Figure 1 shows a photograph of the blade, with an arrow indicating the affected region. The microcracks are observed in the dovetail edge-of-bedding as a network of parallel fine cracks of a nominal depth of 0.005 in. Current usage criteria require inspection of these blades after every 30 hours of service which involves removing blades from the assembly and examining each for microcracks using eddy current techniques. Currently there are no repair or refurbishing options, nor have there been major catastrophic failures reported from these microcracks, yet these blades are retired routinely from service when microcracks are detected in the dovetail edge-of-bedding. A network of parallel microcracks in a band over a width of about 0.1 in and length of about 0.5 in. is seen in Figure 2. This region also showed substantial mechanical damage associated with contact fretting. Figure 3 shows a cross sectional micrograph of a typical microcrack, which is less than 0.005 in. deep.

Figure 1. The 1st stage compressor blade (arrow indicates the fretting damage prone dovetail section).

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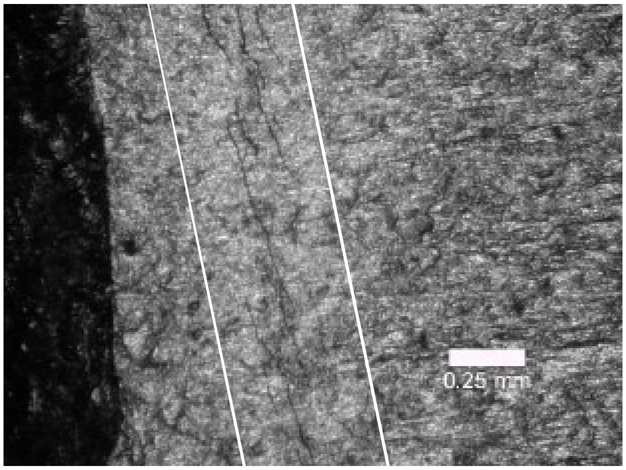


Figure 2. The network of parallel fretting-induced microcracks

Figure 3. Cross-sectional micrograph of a typical microcrack.

LPB has been demonstrated to provide a deep compressive surface layer of sufficient depth to significantly enhance fatigue performance and mitigate fretting fatigue damage,[1] foreign object damage (FOD),[2,3] stress corrosion cracking and corrosion fatigue damage.[4] The LPB process can be performed on conventional CNC machine tools at costs and speed comparable to conventional machining operations such as surface milling.[5]

This paper describes the benefits of applying LPB treatment to fully mitigate the adverse effects of a large simulated crack of nominally 0.020 in. deep, in the edge-of-bedding dovetail regions. The benefits of LPB are two-fold, one to improve the HCF performance, and more importantly, to increase the minimum detectable crack size to nominally 0.020 in., making it possible to use simpler crack detection techniques, without penalty on fatigue life.

Due to the high cost of the blades, approximately \$3,000 each, much of the preliminary LPB process development and HCF testing was conducted using a feature specimen. LPB treatment and HCF testing of a limited number of actual compressor blades followed the successful testing of feature specimens. This study shows that LPB treatment of both feature specimens and blades: (a) improve tolerance to 0.020 in. deep simulated cracks, (b) improve HCF endurance limits by a factor of over 3, and (c) completely mitigate cracking when fatigue tested at design stresses.

The improved HCF performance and microcrack damage mitigation is attributed to the deep, compressive residual stresses generated in the dovetail region of the blade from the LPB treatment. A specific compressive residual stress pattern was achieved by appropriate selection of tooling and LPB treatment parameters. LPB has been shown to provide a cost effective practical means of dramatically improving the tolerance to microcrack damage.

MATERIALS AND METHODS

Ti-6Al-4V (mill annealed) alloy was obtained in the form of 1 in. thick plate. The chemistry and mechanical properties were verified by independent testing. Dovetail feature specimens were fabricated from this plate. Figure 4 shows a feature specimen and a blade together to highlight the similarities between the geometrical features of the specimen and the dovetail section of the blade. All feature specimens were machined and finished with low stress grinding, followed by thermal treatment at 700 C for 1 hr to relieve stresses introduced by machining. The dovetail pressure face (identified both on the feature specimen and the blade in Figure 4) was LPB treated and the resulting residual stresses were measured using x-ray diffraction methods. Figures 5a and b show the LPB processing of the dovetail section of a blade and a processed blade, respectively.

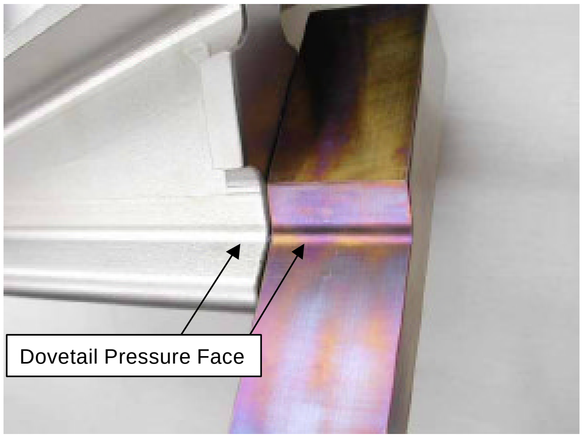
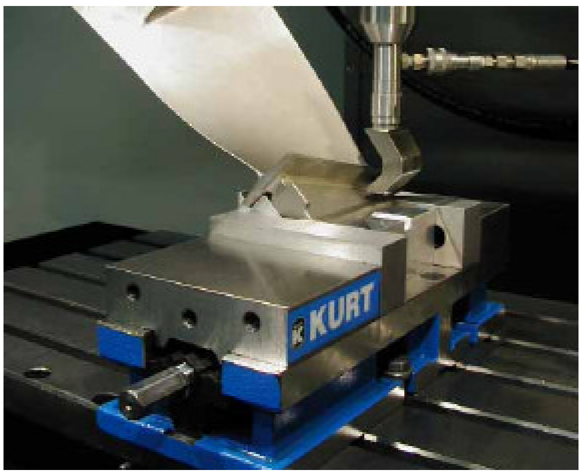


Figure 4. Comparison of the dovetail section of the blade with the feature specimen

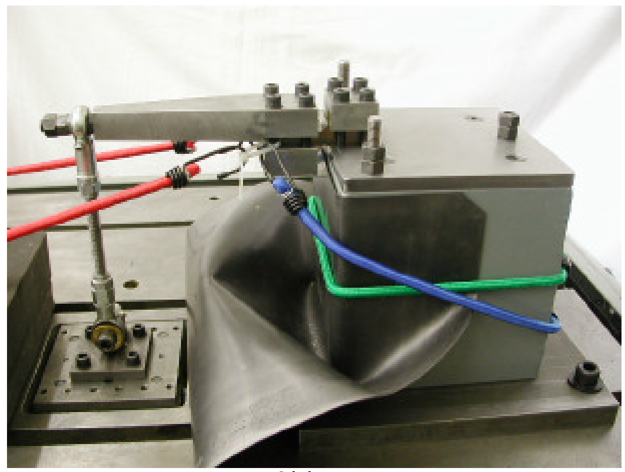


5(a)

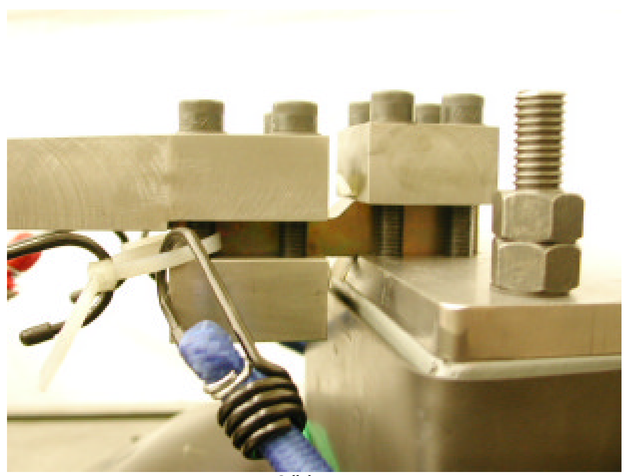
5(b)

Figure 5(a). LPB processing of the dovetail section of the compressor blade, and (b) a close up of the processed dovetail section.

All fatigue tests were performed on a Sonntag SF-1U machine at room temperature at a frequency of 30 Hz. Figures 6 and 7 show the dovetail feature specimen and the actual blade, respectively, loaded in cantilever bending fixtures. All tests were performed at a stress ratio, R, of 0.5. The high stress ratio was chosen to simulate the service condition of the dovetail pressure face. HCF tests were conducted to determine the benefits of LPB treatment to mitigate the presence of an EDM notch, which was introduced at the edge-of-bedding to simulate the fretting-induced microcracks. Photographs showing the details of the EDM notch are shown in Figures 8 a and b.

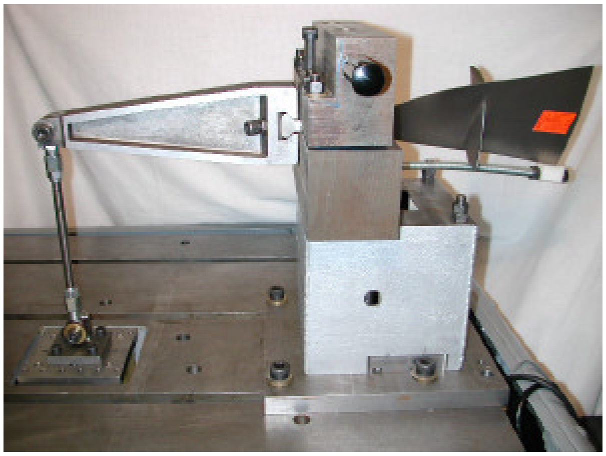


6(a)

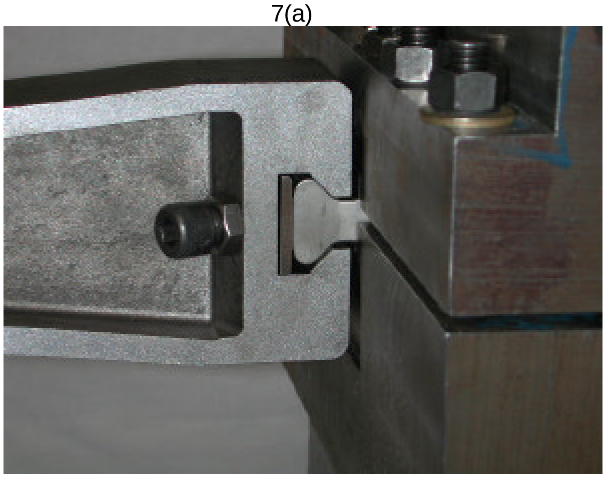


6(b)

Figure 6 (a). Cantilever loading of the feature specimen (b) A close-up view

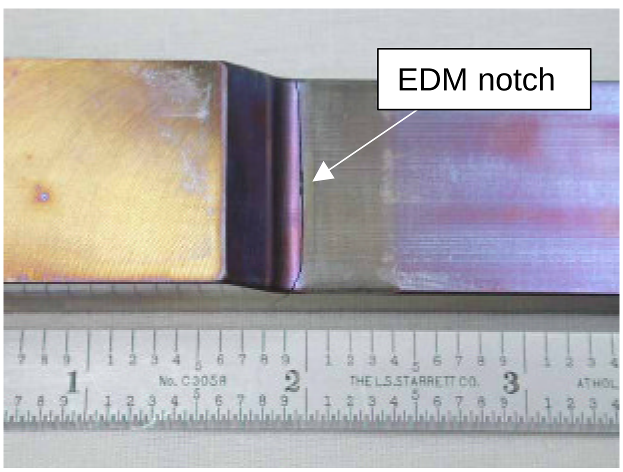


7(a)

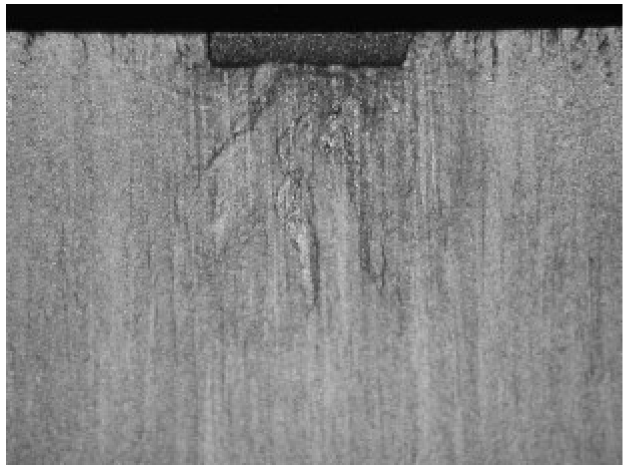


7(b)

Figure 7 (a). Loading arrangement for the blade dovetail section (b) A close-up view



8(a)



8(b)

Figure 8. (a) Location and shape of the 0.020 in. deep EDM notch (b) Cross-sectional view

RESULTS AND DISCUSSION

Figure 9 shows the residual stress as a function of distance from the edge-of-bedding at various depths below the surface of the blade. As seen here, although the LPB treatment was limited to the dovetail pressure face, the beneficial compressive stresses are present in the radial section as well as locations adjacent to the treated region. Compressive residual stresses to a depth of 0.060 in. are evident on the pressure face and the edge-of-bedding. Finite element analysis (FEA) was used to determine the complete distribution of residual stresses, including the locations and magnitude of the compensatory tensile residual stresses as shown in Figure 10. The compensatory tensile stresses are seen to be located in areas that are not normally prone to fatigue or other types of damage.

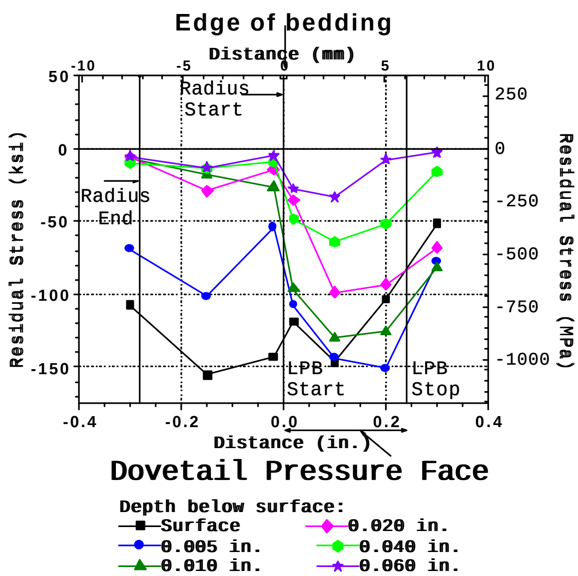


Figure 9. Residual stress distribution on the dovetail section of the LPB treated blade.

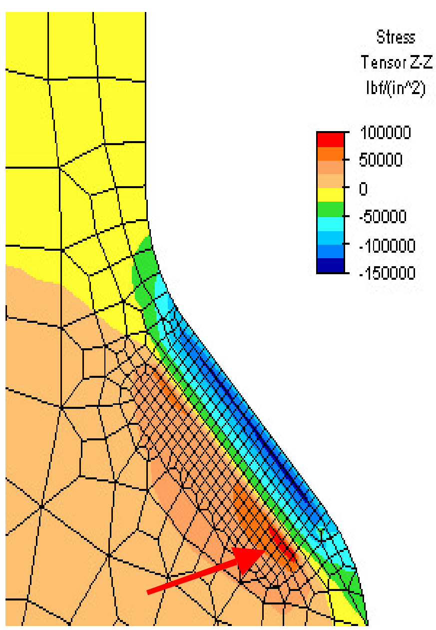


Figure 10. FEA simulation of the residual stresses from Figure 9 identifies the location (red arrow) and magnitude of the compensatory tensile residual stresses in the blade.

Figures 11 and 12 show the HCF test results in the form of S-N data for the feature specimens and the blades, respectively. Although more HCF tests were conducted using the feature specimens, very similar trends are evident in both figures. In Figure 11, a fatigue strength (at 10^7 cycles) of nominally 75 ksi is seen for the baseline, unnotched feature specimens. As shown in Figure 12 for the actual blades the fatigue strength is substantially reduced to about 30 ksi in the presence of a 0.020 in. deep EDM notch. However, even with a 0.020 in. deep EDM notch, both the LPB treated feature specimens and blades show a substantial increase in the fatigue strength of 90 ksi, as compared to the fatigue strength of 75 ksi for the smooth baseline specimens without a notch. The LPB treated feature specimens and blades with 0.030 in. deep EDM notch show a fatigue strength of 60 ksi, and the feature specimens with 0.040 in. deep notch show a fatigue strength of 45 ksi.

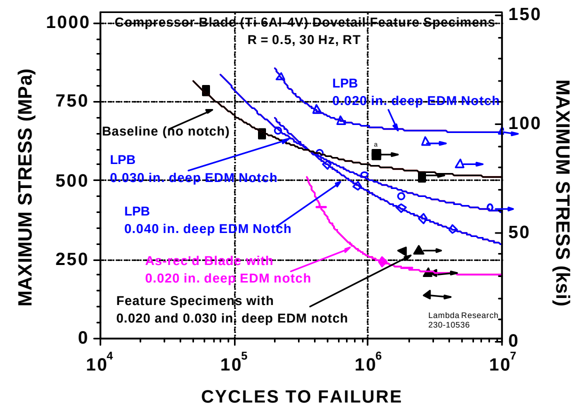


Figure 11. S-N data for feature specimens

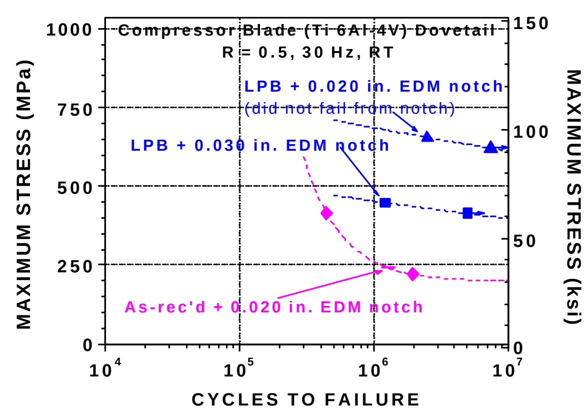
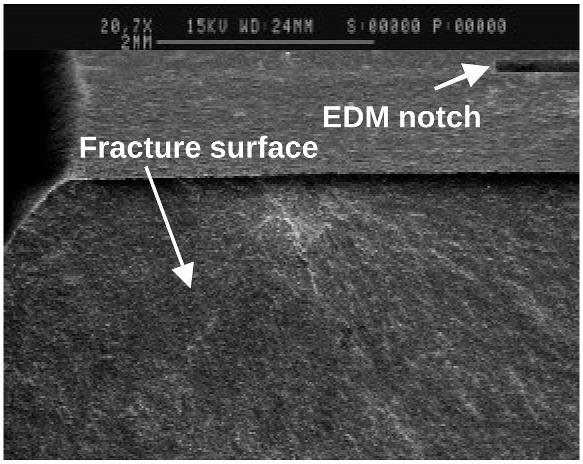


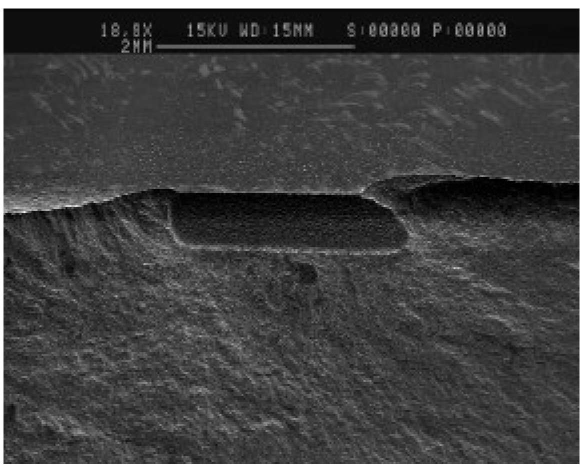
Figure 12. S-N data for blades

Fractographic analyses (Figures 13a and b) show that the LPB treatment was successful in mitigating the cracking from the 0.020 in. deep EDM notch. This specimen failed at 95 ksi after

fatigue loading in excess of 3,000,000 cycles. In the blade with 0.030 in. notch, the fracture process initiated from the notch, and this blade failed at 65 ksi after fatigue loading in excess of 1,000,000 cycles. In comparison, all the baseline feature specimens and blades with 0.020 in. notch failed from the notch at stress levels as low as 30 ksi.



13(a)



13(b)

Figure 13: SEM fractographs of cracking in HCF tested dovetail sections with LPB, (a) shows cracking in the presence of a 0.020 in. deep EDM notch away from the edge-of-bedding, (b) shows crack nucleation from an EDM notch 0.030 in. deep. In both cases, the surface length of the notch is 0.100 in.

SUMMARY

LPB produced a zone of compression in the dovetail region of a 1st stage compressor blade to a depth of 0.065 in. Also, although only the pressure face of the dovetail was treated, compressive residual stresses extended to regions beyond the treated areas. In HCF, LPB processed specimens with 0.020 in. deep EDM notch showed an endurance limit of greater than 90 ksi. This fatigue performance is better than the untreated baseline specimens with and without the notch, 30 ksi and 75 ksi, respectively. LPB treated blades and feature specimens with 0.030 in. and 0.040 in. deep notches showed endurance limits of 60 and 45 ksi, respectively. The compressive residual stresses from LPB extending to depths beyond the depths of the EDM notches are responsible for the improved fatigue performance. Fractographic analyses showed that LPB successfully mitigated the propagation of cracks from a notch of 0.020 in. depth. This implies that the fretting-fatigue induced microcracks of depth less than 0.005 in. can be easily mitigated by the use of LPB treatment.

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